3.3 Renewable Resources: The Economics of the Fishery

A. Introduction

Some historical data:

Figure 1 Canadian fish landings and value


Note that the value estimate is in current dollars. To get a true picture we should deflate the data with a price index like the CPI.
Figure 2 Total World Fishery Production by Region; Source: Food and Agricultural Organization of the United Nations (FAO), [http://www.fao.org/fi/fifacts/plots/default.asp](http://www.fao.org/fi/facts/plots/default.asp)

- major source of protein for many communities
- An important source of employment for some communities and regions
- Technological change has greatly increased catches and reduced costs
  - Nylon filament reduced cost of nets
  - Refrigeration allows catches to be stored onboard
  - Satellites and computer technology to pinpoint fish migrating
- Overexploitation and environmental change such as pollution have caused populations of many important species of fish to decline markedly in the last several decades – e.g. cod, halibut, haddock.
- We may still see increased catches due to lower valued fish being caught.
- Increased conflicts among user groups
- Competition among fishing nations for stocks outside each country’s 200 mile limit
- Conflict between commercial and recreational fisheries.

B. A Model of the Fishery

Simplifying assumptions: a fishery in a particular region with one type of fish harvested by homogeneous vessels all originating from a particular port.

Demersal fish – groundfish – lobster, oysters, flounder, cod

Pelagic fish – migrate over a wide area of the ocean

A renewable resource

Reproductive potential of fish depends on size of fish population and characteristics of habitat – assume habitat characteristics held constant for the moment

Population or stock is measured in biomass (weight) units, not by number of individuals – growth can occur through the production of new individuals or growth of existing individuals.
B.1 Fishery Populations: Biological Mechanics

- assume growth rate of the stock depends on its size
- small population – births outnumber deaths because of large food supply
- as biomass rises deaths rise as food per creature diminishes
- growth rate declines – eventually deaths may equal births and the growth rate falls to zero.
- There may be a minimum size of stock necessary to maintain a viable population.
- \( X(t) \) is the stock of fish

\[
\frac{dX}{dt} = F(x) \tag{1}
\]

\( F(x) \) is the instantaneous rate of growth of the biomass of the fish population
Purely compensatory growth function:

Depensatory growth function:

A growth curve exhibiting critical dispensation:

Logistic Growth Function:

\[ F(x) = rX(1 - X/k) \]  \hspace{2cm} (2)

- \( r \) is the intrinsic instantaneous growth rate of the biomass
- \( k \) is the carrying capacity of the habitat
- Sketch the logistic growth curve in the figure below.
If we integrate $F(x)$ we can solve for $X$ as a function of time:

$$X(t) = \frac{k}{1 + ce^{-rt}}, \quad c = \frac{(k - X_0)}{X_0}$$

(3)
If there is no harvesting we can find the value of $X$ which represents a steady state i.e. $\frac{dX}{dt} = F(X) = 0$

What is this steady state level for the fish stock?

Discrete time analogue:

$$X_{t+1} - X_t = rX_t (1 - \frac{K}{X_t})$$

Can produce complex behaviour depending on value of $r$ – see Conrad and Clark, p. 64 for details.

**B2. Bionomic Equilibrium in a Simple Model**

- an equilibrium that combines biological mechanics with economic activity

- assume harvesting is costless

- How do different harvest rates affect the fish population?
Case I: Mining the fishery – draw a harvest rate (h1) that is everywhere above F(x)

If the $X_0 = k$, what happens to the fish stock once harvesting starts?

Case II: Draw a harvest rate (h2) that allows us to obtain the maximum sustained yield.

If the $X_0 = k$, what happens to the fish stock once harvesting starts?

Case III: Sketch a harvest rate line at $F(X_1)$ – label it h3

What if $X_0 = k$?
What if \( X_0 \) is slightly greater than \( X_1 \)?

What if \( X_0 \) is slightly less than \( X_1 \)?

For \( h_3 \), which stock level represents a stable equilibrium and which represents an unstable equilibrium?

The effects of harvesting on the fish population can be summarized by:

\[
\frac{dX}{dt} = F(X) - H(t)
\]  

(5)

C. Harvest level as a function of effort

- Assume perfectly competitive industry and each firm takes all prices, including factor prices as given and constant over time
- implies demand for fish and supply of factors are perfectly elastic

Define harvesting function \( h(t) \):

\[
H(t) = G[E(t), X(t)]
\]

\[
E(t) = \text{fishing effort}
\]

\[
X(t) = \text{stock}
\]

(6)

Effort refers to an index of capital, labour, energy and material inputs. Eg. Number of lobster traps used.
Consider how $h$ varies with $E$, for a given (steady state) fish stock.

**Figure 4 Harvest versus fishing effort**

Now consider how harvest is affected when the stock is varied given a fixed level of effort.

Harvest will be an increasing function of the fish stock – assume it is linear for simplicity.

A commonly used harvest function is:

$$h(t) = qE(t)X(t)$$  \hspace{1cm} (7)

This function is based on two assumptions:

a) Catch per unit of effort is directly proportional to the density of fish in the sea

b) the density of fish is directly proportional to the abundance, $X(t)$
With effort level of \( E_1 \), what is the steady state fish stock?

What if the effort level is increased?

It is inefficient for the fishing industry to exert a total effort that results in a stock to the left of MSY. Why is this so?

We want to plot total revenue and total cost of fishing versus fishing effort. Suppose:

\[ TC = cE, \quad c \text{ is a constant} \]

\[ TR = Ph, \quad \text{let } P=1 \]

\[ \Rightarrow \quad TR = h \]
Figure 5, Sustainable harvest levels for different levels of effort

E1<E2<E3<E4

**Example: The Schaefer Model**

\[ F(X) = rX(1 - X/K) \]
\[ h(E,X) = qEX \]

In steady state:

\[ qEX = rX(1 - X/K) \]

Solve for X:

\[ X = K \left( 1 - \frac{qE}{r} \right) \]

Substitute back into h=qEX to get:

\[ h = qKE \left( 1 - \frac{qE}{r} \right) \]  \hspace{1cm} (8)
Plot the sustainable yield associated with each of harvest levels.

Note that for sufficiently high effort the yield is zero. \((E \geq r/q)\)

**Figure 6  Sustainable Harvest as a function of effort.**

Since the price of fish is 1, the harvest shown in the above graph is identical to total revenue.

Now add a line showing \(TC = cE\).

**D. Objectives of Management**

- A common objective is to maintain the stock that allows the MSY
- MSY is where \(F'(X) = 0\)
- For the Schaefer model this MSY is as follows:

\[
X_{MSY} = K / 2
\]

\[
h_{MSY} = rK / 4
\]
- MSY policies have been criticized because
  - An overestimate of MSY can lead to depletion or extinction
  - MSY is not sustainable in the long run, because of natural fluctuations in stock
  - May not make sense when 2 or more independent species are being harvested.
  - MSY ignores social and economic considerations
  - MSY ignores nonmarket “preservation” values

General management problem to maximize net social benefits from harvesting the resource.

\[
\text{maximize } \int_0^T U(H(t), X(t))e^{-\delta t} dt
\]

subject to

\[
\dot{X} = F(X(t)) - h(X(t), E(t))
\]

\[
X(0) = X_0
\]

Current valued Hamiltonian

\[
\tilde{H} = U(X, Y) + \mu[F(x) - h]
\]

Necessary conditions of the maximum principle:

(a) \( h(t) \) maximizes \( \tilde{H}(X, H; \mu) \) for all \( t \).

(b) \( \dot{\mu} = \delta \mu - \tilde{H}_X = \delta \mu - U_X - \mu F_X \)

D.1 Constant price

- no preservation value

\[
U(X, E) = ph(X, E) - cE
\]

- Maximization problem:
maximize \( \int_0^T \{ph(X(t), E(t)) - cE(t)\} e^{-\delta t} dt \)  \hspace{1cm} (14) 

subject to 
\[ \dot{X} = F(X(t)) - h(X(t), E(t)) \]  \hspace{1cm} (15) 
\[ X(0) = X_0 \]

We choose \( h \) to maximize \( \tilde{H} \):

\[ \tilde{H} = (p - \frac{c}{qX} - \mu)h + \mu F(x) \]

Suppose \( \mu(t) = p - \frac{c}{qX(t)} \)  \hspace{1cm} (17) 

Differentiate (17) to get:

Use adjoint equation and sub in for \( \mu(t) \):

This gives an expression that defines the solution to our maximization problem. Any \( X \) which satisfies this expression is called a singular solution to the original control problem. The \( X^* \) that satisfies this equation represents the optimal equilibrium stock level.

If we are not at \( X^* \) then the appropriate dynamic adjustment is:

\[ h(t) = \begin{cases} 
0 & \text{when } X(t) < X^* \\
h_{\text{max}} & \text{when } X(t) > X^* 
\end{cases} \]  \hspace{1cm} (18)

Procedure for finding the MRAP solution summarized on page 76 of Conrad and Clark.
D.2 Downward sloping demand curve

\[ U(X, h) = B(h) - cE \]
\[ = B(h) - \frac{cY}{qX} \]  \hspace{1cm} (19)

where \( B(h) = \int_{0}^{h(t)} D(s) ds \).

\[ \tilde{H} = B(h) - \frac{ch}{qX} + \mu[F(x) - h] \]  \hspace{1cm} (20)
E. Open access equilibrium

Figure 7

What level of effort would be expected in the open access fishery?

\[
    h = qEX \tag{21}
\]

\[
    \dot{X} = F(X) - h \tag{22}
\]

\[
    U(X, E) = ph - cE = (pqX - c)E \tag{23}
\]

\[
    h = K \left(1 - \frac{qE}{r}\right) \tag{24}
\]

We can also draw MR, AR, and MC curves.
The open access equilibrium occurs where TR=TC. If TC changes the OA harvest will change. Try finding the OA equilibrium effort and biomass if the parameter ‘c’ increases.

At OAE, TR=TC.

Ph=cE

Divide by h:
P=cE/h
At the OAE, price equals the average cost of harvest.

At the OAE, \( MR < MC \rightarrow \) Economically inefficient

Also if biomass is to the left of that implied by MSY, it is inefficient in a bioeconomic sense. The same harvest could be maintained at a higher biomass of fish.

**D. Socially optimal harvest under private property rights**

Under open access each individual firm (fisher) treats the stock, \( X \), as exogenous.

When a firm exerts additional effort it leads to a lower equilibrium stock and a slightly higher harvest cost for every boat.

This is a *stock effect*, an external cost imposed on other firms that is ignored by each individual firm.

Results in economic inefficiency.

Another possible externality – instead of fixed costs per unit of effort, marginal harvesting costs might depend on the total effort in the fishing industry and on the stock.

*Congestion costs* – another reason the OAE will be inefficient.

Three diagrams on the next page show relevant cost and revenue curves for a sole owner. Identify the private property (PPE) equilibrium and compare with the OAE.
Figure 9
The sole owner will maximize profits by choosing the level of effort where:

\[ \text{Effort, } E \]

\[ \text{Biomass, } X \]

\[ \text{Total revenue and cost, } $ \]

\[ \text{Effort, } E \]

\[ \text{MC} = c \]

\[ \text{AR} \]

\[ \text{MR} \]

\[ \text{Effort, } E \]

\[ \text{Biomass, } X \]

\[ \text{TC} = cE \]
Compare the amount of effort used in an OAE versus a sole owner.

Compare the harvest level under an OAE versus a sole owner.